

THE WORLD OF CHEMISTRY

Program #14

MOLECULES IN ACTION

Producer Stephen Redhead

Air Script: October 31, 1988

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Annenberg/CPB Project Logo and Music

Funder Credits

Shots of a chemical solution,
chemical plant, lab demon-
stration, random molecule
graphic

NARRATOR (MUSIC and NAT
SOUND under):

There's more to this solution than meets
the eye. It's worth \$350,000, for a start,
and the start is what gives it that value,
for this solution makes other chemical
reactions go. It's a catalyst. Giant
chemical plants across the country
wouldn't be feasible without small
amounts of vital and expensive catalysts.
What happens during a chemical
reaction, and what role do catalysts
play? To find out, we must look at
molecules in action.

SUPER: MOLECULES IN ACTION

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH in laboratory

ROALD HOFFMANN (SYNC):

Something is really going on in here. There is a color change and then the bubbling. One substance is being transformed into another one. In my body there are hundreds of chemical reactions going on. Some of them fast, some of them slow, they are influenced by the substances that are there, by catalysts, by temperature. But how is this really happening? Deep within at the molecular level, what is going on? Well, we know that in reactions bonds are broken or made. And we also know that molecules are constantly moving around. Could it be that reactions are simply the consequence of molecules bumping into each other? What a wonderfully simple idea -- that all this complexity in the beaker or in my body could be simply the consequence of random molecular collisions? What's even more amazing is that it's true.

MONTAGE: City street scenes,
cells under microscope, auto
plant, gymnastics, ski acrobatics,
jet planes flying, random
molecule graphic, glider flying,
power lines, hydroelectric plant,
subway, television sets in store
window, cars crashing

NARRATOR (MUSIC and NAT
SOUND under):

We are surrounded by objects in motion.
Motion has always fascinated scientists.
We build machines with moving parts.
And marvel at the grace and power of
our own movements. Moving objects
possess kinetic energy, energy of
motion. The faster an object moves, the
more kinetic energy it has. If we could
peer into the molecular world, we would
see a blur of frenetic activity. The
thermal energy of gaseous molecules
makes them travel at incredible speeds.
It is hard to imagine that nitrogen and
oxygen molecules in the air are moving
at speeds of more than 1500 kilometers
an hour. One form of energy can be
transformed into other kinds of energy.
Energy transformations occur all around
us. In hydroelectric power stations,
kinetic energy of moving water is
converted into electrical energy, which
is then used in thousands of different
ways. (cont.)

NARRATOR cont:

The kinetic energy of moving objects is transformed when they collide. In a car crash, there is an abrupt transformation of kinetic energy into sound, heat, and the kinetic energy of flying debris. In the molecular world, randomly moving molecules, with no way of avoiding each other, also collide. When molecules meet, one of two things happens. They either bounce like billiard balls or they break and reform, becoming different molecules. And this is a chemical reaction.

GRAPHIC: Collisions and energy

NARRATOR (MUSIC under):

Let's look at a specific example. In one step in the formation of hydrogen bromide, hydrogen molecules collide with bromine atoms. If these particles collide with insufficient energy, they simply bounce off each other. If the particles collide with sufficient energy, a reaction will result. Let's see that in slow motion. The two particles approach each other and collide. An activated complex forms, kinetic energy is converted into vibrational energy, an old bond weakens and breaks as a new one forms. The complex then splits to give the products a molecule of hydrogen bromide and a hydrogen atom.

Shots of blasting rock,
balloon lab demo,
archival footage of
Hindenburg

NARRATOR (MUSIC and NAT
SOUND under):

Collision theory helps chemists understand how chemical reactions occur, even the most dramatic ones. But not all collisions result in a reaction. The colliding hydrogen and oxygen molecules in this balloon will not react unless you give them some additional energy. A far more dramatic hydrogen explosion took place on May 6, 1937, over New Jersey. The world's largest hydrogen blimp, the Hindenburg, was preparing to land after another safe Atlantic crossing, but an accidental spark provided the additional energy for a terrifying reaction.

Archival footage
of Hindenburg

RADIO ANNOUNCER (VO):

Within seconds, there was a terrific explosion and brilliant orange flames formed a backdrop for a tableau of death. The Hindenburg's seven million cubic feet of hydrogen gas had ignited. The ship's tail plummeted to the ground.

DS in lab

SUPER: Donald
Showalter

DON SHOWALTER (SYNC):

Now, why did the hydrogen-oxygen reaction require additional energy, that extra push in order to get the reaction to go. Well, the reasoning is that every chemical reaction requires an activation energy. Now, activation energy is the minimum amount of energy needed to initiate a chemical reaction. Now, unless there are enough of the colliding molecules that have sufficient energy to exceed the activation energy, then no reaction will happen. Inside this glass tube is a mixture of two gases, nitric oxide and carbon disulfide. The reaction between those two gases has a fairly high activation energy, so I need to give it some additional energy. Now, in order for you to be able to see this reaction, we're gonna have to dim the lights.

Pole vaulter

NARRATOR (MUSIC and NAT
SOUND under):

Activation energy is like an energy hill. Few reactions will occur unless they are given a push to get them over this hill.

GRAPHIC: Activation
energy diagram

NARRATOR:

Here is an energy diagram showing the endothermic reaction between hydrogen and bromine. The reactants are on the left and the products are on the right. We can represent the activation energy as an energy hill separating reactants from products. In order to react, the colliding particles must have enough total kinetic energy to overcome the activation energy hill. An activated complex forms. Once the activation energy has been overcome, the complex splits and the reaction proceeds to completion, the products are formed.

Shots of furnaces,
blowtorches

NARRATOR (NAT SOUND under):

Collision theory explains the effect of temperature on reaction rates. When you heat a chemical system, the reactants gain energy and move faster. Now the collisions are more energetic, more likely to overcome the activation energy hill. Therefore, more collisions result in a reaction and the reaction rate is increased.

GRAPHIC: Activation
energy diagram

NARRATOR:

If we could lower the activation energy hill, we would get the same effect without having to raise the temperature. The lower the hill, the higher the reaction rate, because less energy is required for collisions to result in a reaction and the formation of product.

MONTAGE: Model with
photographer, fabrics,
aspirin, plastics, interior
and exterior shots of Tennessee
Eastman Kodak plant, oil
platform, gas station, coal

NARRATOR (MUSIC and NAT
SOUND under):

Fabrics, plastics, film, and aspirin. What do all these synthetic products share in common? Tennessee, Eastman Kodak. These products are all made using acetic anhydride manufactured here. There's something even more unusual down there. Local coal provides the chemical raw materials to make acetic anhydride. Yet without this rare South African metal, rhodium, there would be no plant at all. They used to make acetic anhydride from oil. With the rise in oil prices in the early '70s, the company began looking for alternative inexpensive materials. Coal was the obvious choice. (cont.)

NARRATOR cont:

First, it is gasified, producing hydrogen and carbon monoxide. At a later stage, carbon monoxide is reacted with methyl acetate to produce acetic anhydride. It is this crucial step which requires the rhodium. A rhodium compound acts as the catalyst. Catalysts are substances which increase the rate of a reaction without being consumed by the reaction. Catalysts do this by lowering the activation energy.

GRAPHIC: Effect of catalyst on activation energy diagram

NARRATOR:

Here again is our activation energy hill. With a catalyst, a new activated complex forms with a lower activation energy. More colliding molecules now have sufficient energy to overcome the hill, so the reaction rate is increased.

Exterior and interior shots of Tennessee Eastman Kodak, rhodium mining, lab work with rhodium

NARRATOR (NAT SOUND under):

The reaction to produce acetic anhydride has a very high activation energy. Without a catalyst present, the reaction would not be feasible. Rhodium is an extremely expensive and rare metal. It costs nearly \$50,000 a pound. (cont.)

NARRATOR cont:

It is bought as a powder by specialized catalyst companies, and kept under lock and key until it is ready to be used. This batch of soluble rhodium trichloride is worth over \$350,000. Stan Polichnowski is an industrial chemist with Eastman Kodak, and the co-inventor of their rhodium-based catalyst.

INTERVIEW: Stan
Polichnowski, industrial
chemist, Eastman Kodak

SUPER: Stan Polichnowski

STAN POLICHNOWSKI (SYNC):

We don't purchase rhodium metal. We need to purchase a soluble precursor that we can use to make our catalyst. There are companies that will take the metal and convert it to something that we can use directly in our, in our system. An example of that is rhodium trichloride, which we can use to make our catalyst, and it's a dark crystalline material, soluble, so we can make our homogeneous catalyst. From the rhodium precursor, we, in our process, produce an organometallic compound. This is an example of an organometallic compound. And by that I mean it has a central metal atom, with organic ligand attached to it. And in this case, the red are oxygen atoms, the blue are nitrogen atoms of pyridine rings.

Chemist at work in lab,
plant shots

NARRATOR (MUSIC and NAT
SOUND under):

If the rhodium is so expensive, how can it be profitable to use the catalyst in such a large-scale reaction? The answer lies in the fact that catalysts are not used up in reactions. Each catalyst molecule may react with thousands and thousands of molecules of reactant. So this catalyst need only be present in tiny amounts. In addition, as the mixture is drawn off, the catalyst is carefully separated from the acetic anhydride and recycled back into the reactor. Very little rhodium is lost.

INTERVIEW: Stan
Polichnowski cont.

STAN POLICHNOWSKI (SYNC):
Without the development of a viable catalyst system for producing acetic anhydride from methyl acetate and carbon monoxide, we would not have built this complex at all.

Aerial shot of plant

NARRATOR (NAT SOUND under):
Because of their remarkable chemical properties, catalysts are used throughout the industry. Dr. Norman Hochgraf, Vice President, Exxon Chemical.

INTERVIEW: Dr. Norman
Hochgraf, Vice President,
Exxon Chemical

SUPER: Norman Hochgraf

DR. NORMAN HOCHGRAF (SYNC):
Within the petroleum industry, where most of the feed stocks for chemicals come from, catalysts are used to produce motor gasoline, heating oil, and feed stocks for chemicals. And within the chemical industry, catalysts are used not only to purify those feed stocks, but they're also used to polymerize the feed stocks, to make plastics, to make rubbers, and to make synthetic fibers. This industry not only wouldn't be profitable without catalysts, but in a sense, it wouldn't exist. Almost everything we do is the result of catalytic activity, which has been carefully designed, carefully selected, and built into our commercial operations.

RH in laboratory

ROALD HOFFMANN (SYNC):
But there is one problem that not even the most efficient catalysts can overcome. This is that few reactions run in only one direction. Oh, we'd like them to, but nature doesn't cooperate. Most reactions are reversible which means that they run in both ways, from reactant to product and then back again from product to reactant. (cont.)

ROALD HOFFMANN cont:

Both reactions go on at the same time, not in one molecule, but if we have a lot of molecules in a reaction flask, then some of the molecules are going from reactant to product and some of the other molecules are going back to the reactant.

Ski resort shots

NARRATOR (MUSIC under):

Reversible reactions often reach a balance, or dynamic equilibrium, where the rate of the forward and reverse processes are equal and the amounts of reactant and product remain constant. It's like an efficient ski resort. While some people are enjoying the descent, others are riding the chair lift back to the top. Despite all the coming and going, when the number descending equals the number returning on the lifts each minute, then an equilibrium is established. The number of people at the top and bottom of the slope remains constant.

GRAPHIC: Chemical equilibria -- a graphic analogy

NARRATOR (MUSIC under):

Chemical equilibria are based on the same principle. Here's another model. In this hydraulic model, fluid in Tank A represents reactant, and fluid in Tank B represents product. (cont.)

NARRATOR cont:

Let's follow a reversible reaction, beginning with just the reactant. Initially, with a large concentration of reactant present, the forward reaction proceeds quickly. Gradually the forward reaction slows down as the reactant is converted into product, but the reverse reaction now starts to increase as the product concentration rises. Eventually, an equilibrium is reached, the forward and reverse reaction rates are equal, and the amounts of reactant and product remain constant. Here the equilibrium favors the product over the reactant. In another system, the rate of the forward reaction is reduced. Notice the narrower pipe leading from Tank A to Tank B. Now at equilibrium the reactant is favored over the product. So the position of an equilibrium varies under different conditions.

RH in laboratory

ROALD HOFFMANN (SYNC):

Left to their own devices, molecules run reactions in both directions. But when we get into the lab trying to make something, we want the reactions to run in just one direction, forwards. How do we do it? Well the equilibrium system have certain restoring forces built in -- if you disturb it, it responds. (cont.)

ROALD HOFFMANN cont:

For instance, if we have a reaction running and then remove the product, the system will run on to produce more of it. If we raise the temperature, then the system will run in the direction of absorbing the heat. This idea was formulated by the French chemist, Henri La Chatelier in 1884 into the following principle.

Archival photograph of Henri
Le Chatelier

SUPER: If a system at chemical equilibrium is disturbed, that system will respond by attempting to counter the disruption.

NARRATOR:

Le Chatelier's principle is one of the most important in chemistry. If a system at chemical equilibrium is disturbed, that system will respond by attempting to counter the disruption.

RH in laboratory

ROALD HOFFMANN (SYNC):

This principle allows chemists to manipulate reversible reactions.

DS in lab

DON SHOWALTER (SYNC):

Let's see Le Chatelier's principle in action by looking at this reversible chemical reaction. In each of these two beakers, I have two cobalt compounds. In this one, almost all of the cobalt ions are attached to water molecules. That's why it's pink. Over here, in this beaker, almost all of the cobalt ions are attached to chloride ions. That's why it's blue. Now, since this is a reversible reaction, we ought to be able to interchange between these two colors. I want to put some of that pink solution into this beaker. And then I'll add chloride ion. Oh, there's the blue color. And then watch what happens if I add water. It goes back to pink. Le Chatelier's principle tells us that if we add chloride ion, a reactant, then the equilibrium will shift to the product side to use up as much of that chloride as possible. And then if we add water to the system, the equilibrium will shift to the reactant side to use up as much of that excess water as possible.

Chemical manufacturing plant
shots, farm machinery towing
ammonia tank

NARRATOR (NAT SOUND under):
The ability to shift the position of the
equilibrium in every action has
important consequences for chemical
manufacturers. Consider ammonia, the
world's number two industrial chemical.
Most of the 60 million tons produced
annually makes fertilizer. Without it,
farmers would not be able to grow
enough food to feed us all.

EQUATION over plant shot

NARRATOR (NAT SOUND under):
Ammonia is produced by reacting
nitrogen gas with hydrogen gas, quite
straightforward. But there's a problem.
The reaction is reversible.

Plant shots

NARRATOR (NAT SOUND under):
Now, the ammonia manufacturers are
only interested in the product, so using
Le Chatelier's principle, they must
create the conditions to favor the
forward reaction. This horizontal
ammonia converter at IMC's plant in
Sterlington, Louisiana, is one of the
world's most efficient. The nitrogen for
the ammonia reaction is obtained
directly from the air, and most of the
hydrogen comes from natural gas, which
is reacted with steam in this huge
reforming furnace. (cont.)

NARRATOR cont:

The nitrogen-hydrogen mixture is then piped to the ammonia reactor. The process uses an iron-based catalyst. This increases the rates of both the forward and reverse reactions. Therefore, it does not shift the position of the equilibrium. But the equilibrium is sensitive to temperature, pressure, and concentration. So the engineers manipulate these factors to favor the forward reaction as much as possible.

ANIMATED EQUATIONS
over plant shot

NARRATOR (MUSIC under):

First, temperature. The forward reaction is exothermic, heat is released. Now, if we lower the temperature in the reactor, more ammonia is produced as the system generates additional heat.

Shots in laboratory,
plant shots

NARRATOR (NAT SOUND under):

So the reactants enter the reactor at a relatively low temperature, about 590 degrees Fahrenheit. At lower temperatures still, the forward reaction would be favored more. But the rate of the reaction would become too slow. Therefore the engineers compromise between the rate and the yield of the reaction. What about the effect of pressure?

ANIMATED EQUATIONS
over plant shot

NARRATOR (NAT SOUND under):

In the formation of ammonia, one mole of nitrogen combines with three moles of hydrogen to form two moles of ammonia. Therefore, the pressure in the system drops. By increasing the reactor pressure, more ammonia is formed as the system responds by reducing the pressure.

Reactor and plant shots

NARRATOR (NAT SOUND under):

This reactor, then, is run at a very high pressure, over 2,000 pounds per square inch. The gas mixture is passed quickly over the catalyst, withdrawn, and the ammonia removed by cooling. Removal of the ammonia also favors its formation.

ANIMATED EQUATIONS
over plant shot

NARRATOR:

Here again is the ammonia synthesis reaction. If we remove some of the ammonia, the equilibrium shifts to the right as more nitrogen and hydrogen react to moderate that loss.

Reactor and plant shots

NARRATOR (NAT SOUND under):

After the ammonia is removed, the unreacted nitrogen and hydrogen are recycled through the reactor. It is extraordinary that over all, about 99 percent of the reactants are converted to ammonia, a very efficient process, thanks to Le Chatelier's principle.

SUPER: MOLECULES
IN ACTION

MONTAGE: Lab demonstrations,
pole vaulter,
program graphics

NARRATOR (MUSIC under):

To review, chemical reactions occur as a result of molecular collisions. All chemical reactions have an activation energy. In order to react, colliding molecules must have enough kinetic energy to overcome that activation energy. Catalysts speed up reactions by lowering the activation energy. Most reactions are reversible. In a closed system, reversible reactions come to a dynamic equilibrium. According to Le Chatelier's principle, the position of an equilibrium will shift when the system is disturbed, so as to moderate that disturbance.

Archival photograph of
Fritz Haber

ROALD HOFFMANN (VO/SYNC):

The modern industrial synthesis of ammonia was devised by Fritz Haber, a German/Jewish scientist, a university professor.

RH sitting on steps
of building

I want to tell you his story because it illustrates so well how chemistry interacts with the economics and politics of its time. As a young man at the turn of the century, Haber witnessed the agricultural revolution, the systematic use of chemical fertilizers. The natural supplies of these, for instance from South America were limited and so Haber devised ingeniously in 1909 using his knowledge of gas reactions and Le Chatelier's principle, the modern synthesis of ammonia. And he did it just in time to assure Germany's agricultural independence during the first world war, when its supply lines to South America were cut. That same ammonia was used for making explosives. Haber's contributions to mankind were not all positive. A strong patriot, nothing wrong with that, he devoted his intellect and energies during the war to the making of poison gases, to chemical warfare. And his life ended in a personal tragedy. (cont.)

ROALD HOFFMANN cont:

In 1933, the Nazis came to power with a weird baggage of ideology, including anti-semitism. Overnight the great German patriot and chemist Fritz Haber became the Jew Haber. He was forced to resign his post in Berlin. He left the country. The next year he died of a heart attack, let's say it was a broken heart, in exile abroad.

Credits, Closing Montage, Closing Music

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